Journal of the Royal Society of Western Australia, Vol. 61, Part 4, 1979, p. 119-130.

Morphology of small australites from the Eastern Goldfields, Western Australia

by W. H. Cleverly

W.A. School of Mines, Kalgoorlie, W.A. 6430

Manuscript received 22 August 1978; accepted 22 August 1978

Abstract

Forty-two australites (Australian tektites) of average mass about 1/4 g and of forms peculiar to small australites have been examined. Fractionally lower but more variable specific gravities compared with australites in the general size range are attributed to differential vapourization of constituents from these highly thinned forms by aerodynamic heating. Folding of hot glass during flight modified the shapes of some specimens. The morphological series comprising flanged forms, "small" flanged forms and discs or plates has been reviewed and is not seen to be parental to the most abundant type of bowls. An independent bowl series is proposed. There is a need for further studies of small australites if their types are to be more closely defined and their development understood.

Introduction

The general principles of australite morphogenesis are believed to be clear except in the cases of two groups of specimens. One group comprises small forms, generally of mass less than 1/2 g which have no shape counterparts amongst larger specimens; the other group comprises a variety of unusual or rare, so-called "aberrant" forms. This paper is concerned with the first of those two poorly understood groups.

The primary shapes of australites are believed to have originated when small bodies of melt were shaped by surface tension or by an equilibrium between surface tension and the centrifugal force arising from their rotation. The shapes of the cooled and consolidated primary bodies were modified by aerodynamic (secondary) processes during oriented, hypersonic velocity encounter with the earth's atmosphere and by minor breakage upon impact with the ground. The shapes have since been further modified by the terrestrial (tertiary) processes of weathering and erosion.

The shaping effects of aerodynamic processes were size-dependent. Specifically in the case of primary bodies of millimetre dimensions, the formation of flanges was even more important than it was for bodies of medium (1-3 cm) size. However, loss of the aerothermal stress shell beneath the ablation-stripped frontal surface such as occurred spontaneously from large bodies late in flight, or has often been completed as a result of terrestrial temperature changes for those of medium size, did not apply to small secondary bodies which had been aerodynamically heated throughout. The folding of hot, thinned (<3 mm), secondary bodies was a shaping process of some importance only in this small-size category.

The smallest primary bodies were probably entirely destroyed by aerodynamic ablation stripping. Others were reduced to sizes difficult to observe in the field. The small forms which survived the hazards of atmospheric braking have since been subjected to terrestrial destructive processes of various degrees of intensity. Chemical etching to depths of a millimetre or so by the constituents of soil water, which can develop minor sculpture on the surfaces of larger australites, is capable of disintegrating small ones. Abrasion by blown sand or during transport by running water such that a larger specimen is regarded as poorly preserved can modify a small one to the extent that little of morphological interest can be learnt from it. Terrestrial destructive processes have been disproportionately severe on small australites.

The most assiduous collectors of australites at the present time are the Aborigines and those who trade their finds to lapidaries are aware that very small specimens are useless for lapidary purposes. It is known that at least some Aborigines ignore small specimens, small natural fragments and flakes as being unsaleable. Several of the meagre total of 42 specimens which could be assembled for discussion in this paper were the discard from a collection made for sale.

Considering the profound re-shaping during atmospheric transit, the severity of terrestrial destructive processes and the difficulty of observation or intentional disregard of small specimens in the field, it is understandable that so few well-preserved small australites are present in collections and that their morphogenesis is poorly understood. The criticism has been made that much attention has been given to large australites and very little to those at the other end of the scale. The answer to that criticism is that the only known, well-preserved, very small australites deserving of detailed study are those from relatively temperate and humid Victorian localities (Baker 1940, 1963, 1964; Baker and Cappadonna 1972; Birch and Cappadonna 1977; Cleverly 1977). The only recorded Western Australian small australites of the types concerned here are a bowl from the Kalgoorlie region (Baker 1940) and a variety of forms, mostly from Menangina Station (Cleverly 1973), but even the best of specimens from the semi-arid windswept interior warrant no more than brief notes appropriate to their weathered condition. Fenner (1934) has been cited as having recorded the presence of numerous small specimens in the W. H. C. Shaw collection (South Australian Museum) from Israelite Bay and part of the Nullarbor Plain, but all are of shapes represented amongst larger specimens. Bowls and other forms peculiar to small australites were not recorded by Fenner in the Shaw collection.

Material

Some physical details of the 42 specimens examined are shown in Table 1.

The definitions of "broad oval", "narrow oval" and "boat" shapes used in the table are those of Fenner (1940). The procedure adopted for specimens having a core is to classify the specimen according to the shape of the core, and if the shape of the flange differs, to add a rider to that effect. When a core is lacking, the specimen is necessarily named according to the overall shape. When a core is reduced to very small size it is probably no longer a reliable guide to the shape of the primary body but the flange is even less so. At the extreme developmental stages reached by these small australites, flanges tend towards round shape as seen in Fig. 6C where the narrow oval core has a broad oval flange; for further examples see Fig. 6V, W.

Specific gravities were determined by loss of weight in toluene of known temperature using a chemical balance except in the case of specimen No. 12 for which a Berman Balance was used.

The dimensions are stated in conventional manner with length and width measured in directions normal to the line of flight and the thickness parallel to the line of flight. All dimensions are between tangents to the curved shapes. The dimensions of the core, a central remnant of the primary body, are stated in the same way, or in the absence of a core, the thickness of the glass at the anterior pole is given. The overall thickness minus that of either the core or the glass is the depth of the posterior cavity. The average value of (flange width)/(core radius) can be calculated from the dimensions as explained in a subsequent section.

The specimens are the gleanings from more than 26 000 Eastern Goldfields australites dispersed in 20 collections, the majority of which contained no usable specimens. Specifically, the specimens are from the following collections which are indicated in Table 1 by the abbreviations given here; South Australian Museum (SAM); Geology Department, University of Melbourne (UM); Geology Department, W.A. School of Mines (WASM); the private collections of K. Jenkins (KJ), J. L. C. Jones (JLCJ), P. J. Simmonds (PJS); the Tillotson collection (TC) owned jointly by Mr and Mrs R. G. Tillotson and Mr D. J. Tillotson. Australites used for comparative purposes include specimens from the British Museum (Natural History) (BM) and the collection of the late Dr George Baker, now in the National Museum of Victoria (NMV).

Inclusive cf specimens previously described (Cleverly 1973 Nos. 1-20) and 60 which were rejected as being too broken or weathered to be informative, the small specimens constitute less than 0.5% of the Eastern Goldfields australites available for inspection. For reasons of observation and collection, the sample is insufficiently representative of the true proportion of these small forms and is most unlikely to contain the full variety of shape types.

Small australites occur at only a few of the numerous Eastern Goldfields localities from which australites have been recorded; those mentioned in Table 1 are shown in Figure 1. The locality "Kalgoorlie and district" warrants comment. That, or a similar locality attribution is found in the registers of at least five official collections for australites obtained from several early private collectors or from their estates. Some individual australites in those collections are known to have been found far distant from Kalgoorlie. In my opinion, "Kalgoorlie and district" reflects only the known fact that all of the private collectors concerned were residents of Kalgoorlie, though it is probable that the specimens were found somewhere in the Eastern Goldfields which were being actively prospected when the collections were made.

Unless otherwise stated, illustrations show the australite in flight orientation with the line of flight vertically downward. The plan view therefore shows the posterior surface of flight. In elevational views and vertical sections, "downward" means towards the bottom of the page.

Specific gravity

Specimen No. 8 has the anomalously low specific gravity 2.355 which is visibly attributable to bubble cavities. It has therefore been omitted from further consideration in this section.

Table 1

Shapes, physical details and sites of finds of small australites from Eastern Goldfields, Western Australia

No.	Collection	Shape	Mass (g)	S.G.	Overall dimensions (mm)	Core dimensions (mm)	*Thickness (mm)	Locality
1	SAM T451	"Small" button or cored disc, gently folded	0·172 1	2·437	8·1 x 6·6 x 3·6	2·9 x 2·2 x 2·0	....	Kalgoorlie or district
2	TC	"Small" button, gently folded	0·136 2	2·390	8·3 x 7·8 x 2·0	c4 x c3·5 x 1·6	....	Vicinity of Seven Mile Hill
3	KJ	Round bowl, "core" defined only by texture	0·108 7	2·441	(7·2–7·0) x 2·6		1·5	c 20 km W.S.W. of Mt. Remarkable H.S.
4	SAM T451	Round bowl, incipient folding	0·077 6	2·414	(6·2–6·0) x 2·1		1·5	Kalgoorlie or district
5	SAM T451	Round shallow bowl, slightly folded	0·121 3	2·402	7·1 x 6·5 x 2·4		1·8	Kalgoorlie or district
6	TC	Cored round bowl, about half folded	0·317 5	2·427	9·9 x 6·2 x 6·2	Not determinable		Vicinity of Seven Mile Hill
7	PJS 75	Cored round or slighly oval bowl, about half folded	0·356 3	2·431	9·9 x 7·1 x 5·7	Not determinable		c 10 km E. of S. from Widgiemooltha
8	JLCJ	Round or slightly oval bowl, about half folded, asymmetrically, core defined only by texture	0·197 7	2·355	8·7 x 7·1 x 4·1	Not determinable		Eastern Lake Yindarlgooda
9	KJ	Shallow round bowl, posterior surface almost flat	0·352 1	2·438	(10·0–9·6) x 3·4		2·7	c 20 km W.S.W. of Mt. Remarkable H.S,
10	KJ	Shallow round bowl, slightly folded	0·449 8	2·437	9·9 x 9·2 x 5·2		3·5	c 20 km W.S.W. of Mt. Remarkable H.S,
11	TC	Shallow round bowl	0·246 8	2·386	(9·1–8·5) x 3·5		2·8	Vicinity of Seven Mile Hill
12	SAM T561	Shallow, flat-cored, round bowl	0·058 4	2·440	(6·8–6·2) x 1·8	(4·3) x 1·4		Kalgoorlie or district
13	JLCJ	Shallow round bowl	0·419 4	2·439	(10·0–9·6) x 4·1		3·8	Central or north Lake Yindarlgooda
14	WASM 10 873	Cored broad oval bowl	0·235 2	2·437	9·3 x 8·0 x 3·4	5·6 x 5·0 x 2·6		Kalgoorlie district
15	TC	Broad oval shallow bowl, cored	0·240 4	2·427	9·2 x 8·9 x 2·8	4·2 x 5·0 x 2·4	1·9	Magnesite Ck., c 4 km E. of Bulong
16	JLCJ	Broad oval bowl	0·529 6	2·456	11·6 x 9·4 x 4·2		3·0	Eastern Lake Yindarlgooda
17	JLCJ	Broad oval bowl (fractured)	0·251 1	2·462	9·0 x 7·2 x 4·0		2·5	Central or north Lake Yindarlgooda
18	WASM 11 774	Broad oval shallow bowl, slightly convex core, boundary undefined	0·363 2	2·420	10·1 x 9·6 x 3·3		3·2	c 20 km W.S.W. of Mt. Remarkable H.S.
19	TC	Broad oval shallow bowl, core poorly defined ..	0·374 6	2·409	11·0 x 9·9 x 3·5	6·9 x 5·3 x 3·0		Taurus, N.E. of Bulong
20	KJ	Broad oval shallow bowl	0·296 2	2·465	10·4 x 9·4 x 2·7		2·2	c 20 km W.S.W. of Mt. Remarkable H.S.
21	WASM 11 775	Broad oval shallow bowl, very gently folded .	0·239 1	2·435	9·2 x 7·9 x 3·6		2·5	c 15 km S.S.E. of Mt. Remarkable H.S.
22	TC	Broad oval plano-convex form	0·108 1	2·399	7·4 x 7·0 x 1·7		1·5	Vicinity of Seven Mile Hill
23	TC	Broad oval plano-convex form	0·060 2	2·403	7·0 x 5·4 x 1·3		1·1	Vicinity of Seven Mile Hill
24	KJ	"Small" flanged narrow oval with broad oval flange	0·188 3	2·465	8·8 x 8·3 x 2·3	5·0 x 3·3 x 1·8		c 20 km W.S.W. of Mt. Remarkable H.S.
25	KJ	Narrow oval bowl	0·145 6	2·435	9·0 x 6·0 x 3·0		1·5	c 20 km W.S.W. of Mt. Remarkable H.S.
26	SAM T561	Narrow oval bowl, slightly asymmetrical	0·159 8	2·446	9·1 x 6·4 x 3·0		1·6	Kalgoorlie or district
27	TC	Narrow oval bowl	0·263 0	2·457	10·7 x 6·6 x 3·5		1·8	c 6 km N. of Kanowna
28	KJ	Narrow oval bowl, slightly asymmetrical and slightly folded on transverse axis	0·148 1	2·440	8·0 x 5·0 x 3·9		3·4	c 20 km W.S.W. of Mt. Remarkable H.S.
29	SAM T451	Narrow oval bowl	0·080 8	2·385	6·6 x 4·3 x 2·4		1·6	Kalgoorlie or district
30	KJ	Narrow oval "tray" with thickened rim	0·376 9	2·450	16·6 x 9·2 x 2·7		1·6	c 20 km W.S.W. of Mt. Remarkable H.S.
31	SAM T561	Narrow oval "tray" with thickened tim	0·147 6	2·425	12·7 x 8·9 x 1·4		0·6	Kalgoorlie or district
32	JLCJ	Cored narrow oval bowl with broad oval flange	0·182 8	2·419	8·7 x 7·7 x 2·9	4·0 x 2·7 x 2·1		Eastern Lake Yindarlgooda
33	KJ	Boat-shaped bowl	0·098 4	2·429	9·8 x 4·2 x 3·0		1·2	c 20 km W.S.W. of Mt. Remarkable H.S.
34	TC	Boat-shaped bowl, slightly folded transversely	0·141 9	2·444	8·9 x 4·6 x 4·2	c 3 x c1 x 2·0		Vicinity of Seven Mile Hill
35	TC	Boat-shaped, "massive" type	0·423 0	2·436	> 13·8 x 6·7 x > 5·8		3·2	Vicinity of Seven Mile Hill
36	WASM 12 004	"Small" flanged teardrop with broad oval flange	0·128 3	2·417	8·2 x 7·6 x 2·1	5·1 x 4·3 x 2·0		10 km E. of Menangina H.S.
37	SAM T451	"Small" flanged teardrop with oval flange (fractured)	0·219 9	2·432	> 12·0 x > 7·9 x 2·5	c 9·3 x 3·8 x 2·4		Kalgoorlie or district
38	KJ	Shallow teardrop bowl with thickened rim and overfolded tail	0·131 1	2·394	9·0 x 6·9 x 2·6		1·7	c 20 km W.S.W. of Mt. Remarkable H.S.
39	KJ	Shallow teardrop bowl with thickened rim, part of overfolded tail	0·236 2	2·444	> 10·6 x 9·1 x 2·2		2·0	c 20 km W.S.W. of Mt. Remarkable H.S
40	TC	Shallow teardrop bowl	0·135 5	2·397	11·8 x 6·0 x 2·5		1·5	Vicinity of Seven Mile Hill
41	PJS 177	Shallow teardrop bowl with partial frontal collapse	0·348 6	2·446	12·8 x 9·5 x 2·6		1·5	Boomerang Lakes, c 10 km S.W. of Menangina H.S.
42	UM	Aberrant with teardrop flange	0·224 1	2·429	10·4 x 9·1 x 2·6		1·5	Kalgoorlie district

* Glass thickness at the anterior pole.

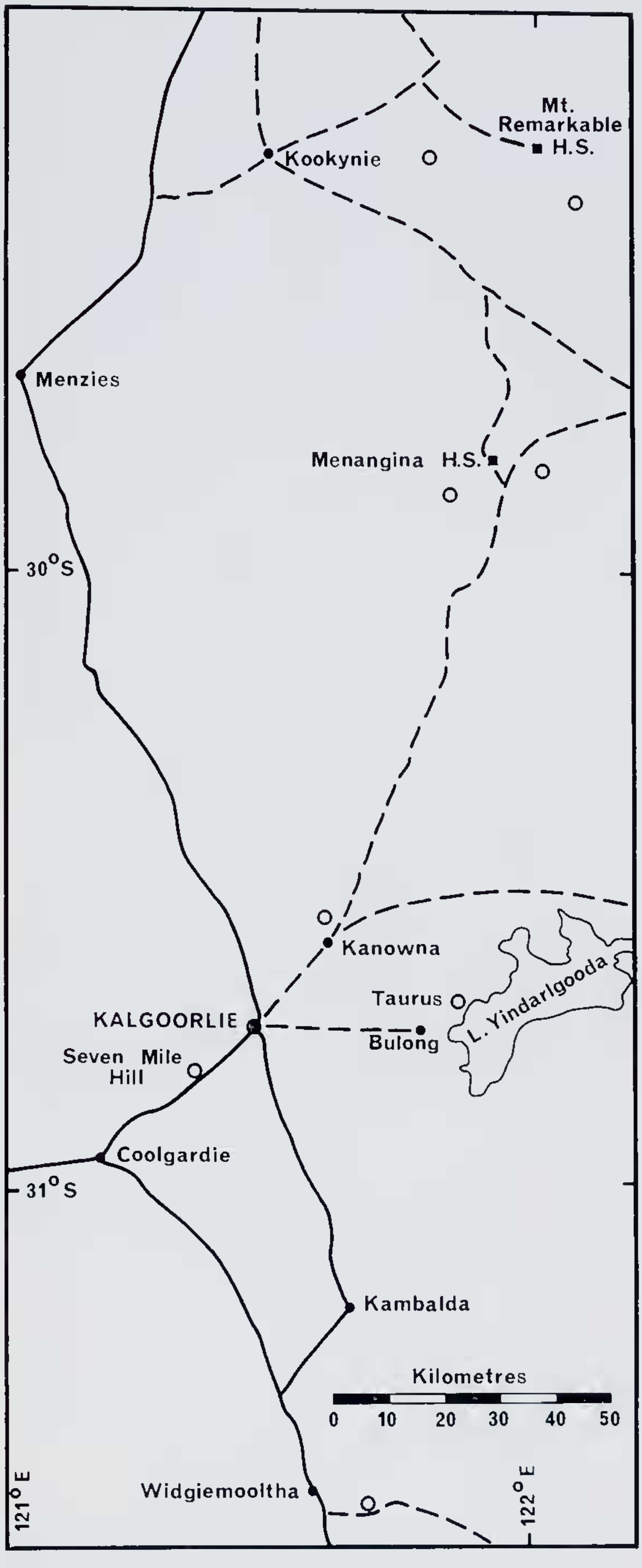

Figure 1.—Part of the Eastern Goldfields of Western Australia showing sites of finds of small australites (open circles) in relationship to major roads. Unsealed roads shown by broken lines.

The relative frequency polygon of specific gravity for a sample of 420 australites from the Kalgoorlie Area given by Chapman *et al.* (1964)

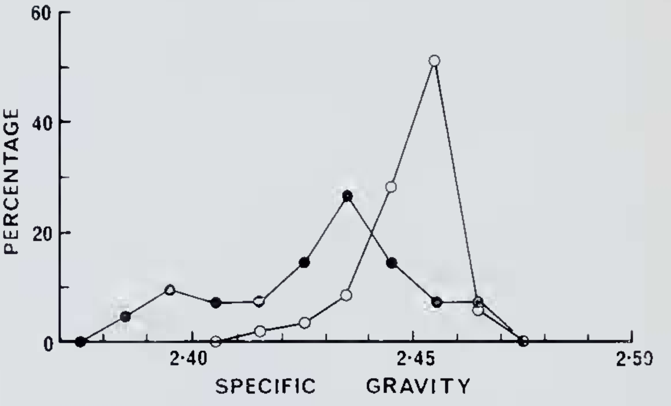

Figure 2.—Relative frequency polygons of specific gravity for australites. Open circles: polygon for 420 australites from the Kalgoorlie Area (Chapman *et al.* 1964). Solid circles: polygon for 41 small Australites from the Eastern Goldfields (this paper).

is reproduced in Figure 2. It shows a very clearly defined mode in the 2.45-2.46 interval. The polygon for the 41 small specimens is somewhat irregular, the mode is in the lower interval 2.43-2.44 and less defined, the whole polygon being flatter and extending down to lower values of specific gravity. The irregularity was to be expected because of the small numerical size of the sample, and the other features are understandable because secondary ("flange") glass has slightly lower specific gravity than core or body glass (Baker and Forster 1943). The lower value may be attributed to differential vapourization of constituents such as potassium with consequent residual enrichment in some lighter but less volatile constituents such as magnesium and aluminium (Lovering 1960). The proportion of secondary glass in these small specimens is evidently sufficient for its lower specific gravity to affect the value for the specimen as a whole. Such an effect is insignificant in larger specimens, even when they retain a substantial part of the flange. The proportion of secondary. glass present is also very variable. Some specimens consist almost entirely of secondary glass and have therefore been strongly heated throughout. Hence the lower but more variable specific gravity values when compared with specimens representative of the general size range.

Role of folding in australite morphogenesis

During the later part of the aerodynamic shaping process when deceleration caused by air resistance approached a maximum, the shapes of small secondary bodies were sometimes modified by the folding of hot thinned glass. It will simplify the subsequent discussion if those morphological features which can be attributed with confidence to folding are first summarized. Three general types of failure by folding have been observed.

1. Frontal collapse of thin plates and bowls is seen as a dimple, not necessarily centrally located, or as a more extensive shallow concavity when a flow ridge or thickened rim provided a slightly stronger frame to limit the area of collapse. Partial frontal collapse is shown by a

number of the specimens under examination. Better examples are shown in Figure 5A-C, E. A dimple in the thinned frontal glass over a bubble cavity is not unusual (Fig. 5D) but is not confined to small australites. This feature may be present on any specimen which still has its anterior surface of flight i.e. has not lost the aerothermal stress shell or been too severely eroded. Failure of this kind is aided by the near vacuum conditions within the bubble cavity.

2. Backward folding of secondary structures is shown by the slender "tails" of teardrop specimens (Fig. 6N); more dubious examples from which the hinge may have been broken or eroded away are shown in Figure 6 O, P and very doubtfully in Fig. 6R. The frail "wings" (end-flange) of pine-seed forms (Skeats 1915) may be folded backward and moulded to the shape of the body (Fig. 5F). Some of these features were so frail that they would be readily broken on impact or by subsequent terrestrial erosion processes. In consequence, they are known principally in a folded condition and then only by those parts which are fused to the body of the australite. Because these australites were so thin they were heated throughout and folded parts making contact were fused together. Again, there is an exception amongst larger specimens. Very rarely, full-sized buttons show partial detachment of the flange which is smeared backward to result in a fold undulation in its posterior surface. Two views of such a specimen have been illustrated by Fenner (1934 pl. IV).

3. Backward folding on a hinge of the opposing parts of a complete form is shown by a variety of round and elongated specimens. Folding is usually only partial in thicker specimens (2-3 mm) but may be complete in the thinnest ones (1-2 mm). If the hinge is symmetrically located and the folding complete (like a butterfly with wings closed upward), the posterior surface of flight is no longer visible. The folding of round and slightly oval forms is usually on a diametral or approximately diametral hinge. The earliest stage is seen as a gentle regular undulation of the rear margin (Fig. 4 B(1), B(2), G(1) and others). When folding had advanced further, the sides are distinctly higher than the ends of the hinge (Fig. 4 H(2), Fig. 5K, L). No specimens in which folding was more than half completed are available from the Eastern Goldfields, but more completely folded specimens are available from other localities. Contact between the approaching sides was usually made first at the mid-points of the "lips" whilst the "ends of the mouth" allowed the escape of air enclosed between the sides. With essentially complete folding, only gas escape tubules remained (Fig. 4L(1)), or the sides are in contact except for a disconnected trail of trapped and flattened bubbles (Cleverly 1977 Fig. 1A). The hinge was not always symmetrically placed or at right angles to the length of elongated specimens. This has been illustrated by a broken elongated specimen with edge thickened by overflow (the "tray" type referred to in a later section), which has been folded on a longitudinal hinge about one third of the way across the width (Fig. 5G).

Folding is more difficult for a bowl than for a disc-like form where the hinge is within a plane and allows the two parts to fold over into complete contact. During folding of bowls or any trough-like feature such as the "wings" of pine-seed forms, the curved hinge tends to straighten, causing bulging at the ends (Fig. 5F). Complete contact between the sides is possible only if they are flattened, which necessitates further distortion of the form (Cleverly 1977).

Folding poses a minor problem in nomenclature because it is usual to name australites according to their shapes and proportions in plan view. Folding changes the proportions; length and width may even interchange locations if the hinge is transverse to the original length. Though an object should be named for what it is rather than for what it is thought to have been, it appears preferable in the present instance to make a few measurements and estimate the pre-folding proportions. It would be thoroughly misleading if the specimen shown in Fig. 4L(1) were described as a dumbbell instead of as a tightly folded round form.

Discussion

The development of small australites was envisaged by Baker (1958) as involving first the formation of "small" buttons which, with further growth of flange at the expense of core, became cored discs and thence discs. The thinnest discs then bent backward into bowl-shaped forms. The elongated equivalents behaved in analogous fashion.

The formation of buttons is well documented and experimentally demonstrable (Chapman and Larson 1963). Continued development into "small" buttons is likely because of the short time needed to reach the flange-forming stage i.e. the time when the ablation-stripped frontal surface encroached upon the "equator" of the primary body. The characteristics of "small" buttons (Baker 1958) are that the flanges are more flattened and constitute a greater proportion of the form than on buttons of ordinary size. It may be added that because of flange growth at the expense of core, the posterior pole of the core may be level with or fractionally below the posterior surface of the flange. The cores of six small buttons previously recorded (Cleverly 1973) are 0.2-0.6 mm below the flange. The further transition of "small" buttons into cored discs, the more exaggerated version of the same form and thence into discs are also understandable as the flange developed at the expense of core which became smaller and thinner (Fig. 4A to C).

The width of flange relative to core radius, which will be expressed here as F/C, could be used to make the distinction between "small" flanged forms and discs or their elongated equivalents (plates), if indeed such a distinction is justified. Some authors have tabulated flange width but there is a simpler arithmetical approach using the data of Table 1. The required ratio is (overall diameter-core diameter)/(core diameter), or more simply, (overall diameter)/(core diameter) minus unity. For example, (overall diameter)/(core diameter) for six small buttons (Cleverly 1973 Table 1) is 1.74-1.99, and hence F/C is 0.74-0.99. For specimens having elongated core and/or flange, the averages of length and width may be used. Thus the "small" flanged oval and teardrop specimens shown in Fig. 6C and W have F/C 1.06 and 0.68 respectively.

Most of the disc, plate and bowl forms from Victoria described by Baker (1963) have F/C in the range 1-8 with mean value 2.9. The Victorian specimens described by Dunn (1916), as judged from rather small illustrations, show a similar range of F/C, except that in two specimens the core has almost disappeared. As the core dwindled to disappearance F/C would tend to infinity. The posterior profiles of the flanges are generally flat to concave, reflecting the high ratio of frontal area to mass and resultant severe deceleration (Chapman 1964).

Cored discs of the general style of those known from Victoria occur also in South Australia on Myrtle Springs Station where there have been unusually favourable conditions for their preservation (Corbett 1967 Fig. 5; Lovering *et al.* 1972 pl. 27). As estimated from the illustrations, they have F/C 1.2-2.7.

A comparison has been made in Table 2 between some of the disc and cored plate specimens described by Baker (1963) from Victoria and Western Australian material.

Pair 1. Though the specimens are of comparable mass and overall dimensions, the core of the "small" button is much the larger and this shows up in the F/C value. (See Fig. 6T and U.)

Pair 2. Mass, overall and core dimensions are reasonably comparable and the F/C values are the same. The only difference here is in opinions on nomenclature.

Pair 3. No Eastern Goldfields specimen of comparable mass was available, but the specimens are superficially much alike (Fig. 6V and W). In spite of the smaller mass and overall dimensions of the Western Australian specimen, its core is the larger in all three of its dimensions, which shows up in the F/C value.

Pair 4. Again, no specimen of comparable mass with the Victorian one was available. Other remarks apply as for Pair 3.

The impression may have been gained that the relatively fragile Victorian discs and plates would be distinguishable by small mass. In fact, the average mass of the 29 specimens recorded by Baker (1963) is 0.246 g and of the 42 Eastern Goldfields specimens examined is 0.226 gram. Two of the specimens described by Baker are heavier than any of those included here. After allowing 10% for the greater weathering and fracture losses from the Western Australian specimens, the average masses would not be significantly different. Lighter specimens are known from Victoria (Birch and Cappadonna 1977) but are not as appropriate for comparative purposes as those described by Baker.

From a comparison of the mean masses, it would be expected that the average dimensions of the Victorian specimens would be only fractionally larger, but their lateral dimensions average nearly 13% greater and plan view areas therefore about 27% greater, confirming their relative thinness and fragility.

I can see no natural divisions between buttons, "small" buttons and cored discs nor between their elongated equivalents. Most named specimens in literature would conform to the following values of F/C:—

Flanged forms	<0.7
"Small" flanged forms	0.7-1.0
Cored discs and plates	>1.0

These figures are not suggested as arbitrary definitions, but may be taken as a guide to past practice.

The problem of making a bowl out of a disc by the backward bending of flange as envisaged by Baker (1958) is somewhat akin to closing an umbrella without making use of the folds. The analogy is not as crude as might be supposed, because whilst the hot glass had the advantage of plasticity, it almost certainly had a major disadvantage in the shortness of the time available. The period of ablation flight of the

Table 2

Dimensions and masses of some small australites from Victoria and Western Australia

Pair No.	Registered number	Shape	Mass (g)	Overall dimensions (mm)	Core dimensions (mm)	*F/C	Reference
1	†NMV E7830	Cored disc	0·250	(9·8–9·6) x 2·6	(2·8–2·6) x 1·7	2·7	Baker 1963 No. 1
1	WASM 10 869	"Small" button	0·263	(9·5–9·2) x 3·0	(4·8) x 3·0	0·9	Cleverly 1973 No. 4
2	NMV E7836	Cored disc	0·127	(8·4–8·1) x 1·9	c 4·5 x c 4 x 1·4	0·94	Baker 1963 No. 7
2	WASM 10 609	"Small" button	0·146	(8·3–8·0) x 2·2	(4·2) x 2·0	0·94	Cleverly 1973 No. 6
3	NMV E7837	Teardrop plate with broad oval flange	0·309	10·6 x 9·9 x 2·8	4·5 x 3·2 x 1·7	1·7	Baker 1963 No. 9
3	WASM 12 004	"Small" flanged teardrop with broad oval flange	0·128	8·2 x 7·6 x 2·1	5·1 x 4·3 x 2·0	0·7	No. 36, this paper
4	NMV E7821	Frontally collapsed broad oval bowl	0·636	15·9 x 14·9 x 2·9	5·0 x 4·4 x 1·7	3·3	Baker 1963 No. 12
4	TC	Broad oval bowl	0·375	11·0 x 9·8 x 3·5	6·9 x 5·3 x 3·0	0·7	No. 19, this paper

* F/C signifies (Flange width)/(Core radius). † Victorian specimen is the first of each pair.

much larger, full-sized buttons from Victoria has been estimated as about 12 seconds (Baker 1967), though the bodies would have remained hot a little longer until velocity was checked to the level when heat input lagged behind heat losses. It is a rough rule of thumb that the australites would be stopped by encounter with their own mass of air (O'Keefe 1963); the time available for the development of small australites would therefore be significantly less than 12 seconds. Alternatively, one might think in terms of the aerodynamic drag equation in which deceleration is given by an expression having frontal surface in the numerator and mass (dependent upon volume) in the denominator i.e. having a linear measurement in the denominator. Other things being equal, a button 10 mm diameter would experience at any particular moment twice the rate of deceleration of one 20 mm diameter.

It seems likely that by the time a sphere was reduced to the flange-forming stage and passed progresssively through the button, "small" button, cored disc and disc stages, there can hardly have been more than a second or two during which it could be converted into a bowl. Yet crumpled bowl walls have not been reported, though bowls are the commonest of all small forms. Most of the observed folding was on a hinge. Folding of that kind must also be fitted into the available time unless it occurred after ablation-stripping ceased. This is a possibility because heating of the body of the form as distinct from a surface film may have been more effective when hot melt was not being stripped away almost as fast as it was formed, and for at least a short time, deceleration was still high.

Nor do bowls appear to have developed from "small" flanged forms. There are shallow bowl-like specimens which have the typical wide flange of the "small" form, but they are the result of folding on a hinge (see Fig. 4B(1), B(2)).

Another series of shallow bowls may be of more significance. These have low thick walls directed obliquely backward. Some retain a gently convex core which is not clearly demarcated from the walls (Fig. 4F, G), whilst others have a flat or gently concave posterior surface (Fig. 4I). In no case does a core persist when the depth of the posterior cavity exceeds 1 mm though the trace of a groove (Fig. 4H) or a difference in texture (Fig. 5J) may indicate the former presence of a core. For each of these variants, some folding on a hinge may have occurred (Fig. 4, side branches to right) and for the thinnest specimens, folding may be complete (Fig. 4L(1)). Presumably, frontal collapse occurred only when the form had become highly thinned; a possible example from Victoria is discussed below.

Many bowls thus appear to be independent of the button-disc series and to have developed by the obliquely backward growth of secondary glass constituting the walls. There would then be at least two developmental lineages of small australites which were distinct from the beginnings of aerodynamic shaping. A possible parental candidate for the bowl series is the button with strongly convex posterior profile of flange. Perhaps significantly, such buttons and elongated equivalents are common on Mt. Remarkable and Menangina Stations which have also provided many of the smaller specimens. It is easy to arrange a morphological series linking these buttons to cored bowls (Fig. 4D to G), but it cannot be assumed that such a series is also a developmental lineage.

There may also be a relationship between bowls and pseudo-discs as the result of frontal collapse of bowls. A specimen described and figured by Baker (1963 No. 12) may be interpreted as an example of extensive frontal collapse limited by a prominent flow ridge (Figs. 4L, L(2), 5E); other possible examples are Baker's Nos. 15, 20. Frontal collapse, like the dent in the top of a hat, requires that portion of a thin curved shape should be "turned inside out". In effect, it is a failure on a circular hinge, and the reason for it rather than for folding on a diametral hinge is probably seen in the ribbing provided by flow ridges or thickened edges.

Not only are the origins of bowls in doubt—and are perhaps multiple—but there is no precise definition of the form itself. The only natural

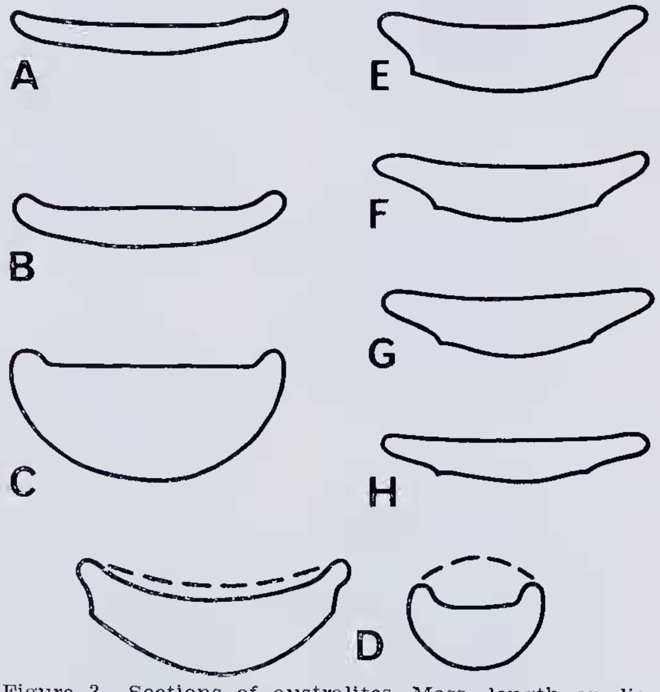

Figure 3.—Sections of australites. Mass, length or diameter, locality and ownership of numbered specimens are given in Table 1. A.—Tray-like form with incipient frontal collapse. No. 30, Table 1. B.—Tray-like form, mass 0.546 g, length 15.2 mm, Menangina Station, W.A. (WASM 10 613). C.—Broad oval of "massive" type, 0.231 g, length 7.3 mm, Earaheedy Station, W.A. (WASM 10 566). D.—Longitudinal and transverse sections of elongated form of "massive" type, profiles added to sections as broken lines. Right hand end of longitudinal section restored. No. 35, Table 1. E.—Thick form approximating to the plano-convex type. No. 11, Table 1. F.—As for E. No. 20, Table 1. G.—Plano-convex form, posterior cavity 0.2 mm deep. No. 23, Table 1. H.—Plano-convex form, posterior cavity 0.2 mm deep. No. 22, Table 1.

point of distinction would be when the posterior pole of the core was reduced below the level of the flange, but this distinction is not seen to have been uniformly applied in the literature. Fortunately, the somewhat artificial distinction between "small" flanged forms and discs has not been applied to bowls as an unnecessary complication.

Other general shapes are represented amongst small australites from Western Australia, though they appear to be rare in eastern Australia, or at least, unreported.

1. "Tray" forms which are thin and extensive with rim thickened by a flow ridge or by overflow of melt from the anterior surface to form a

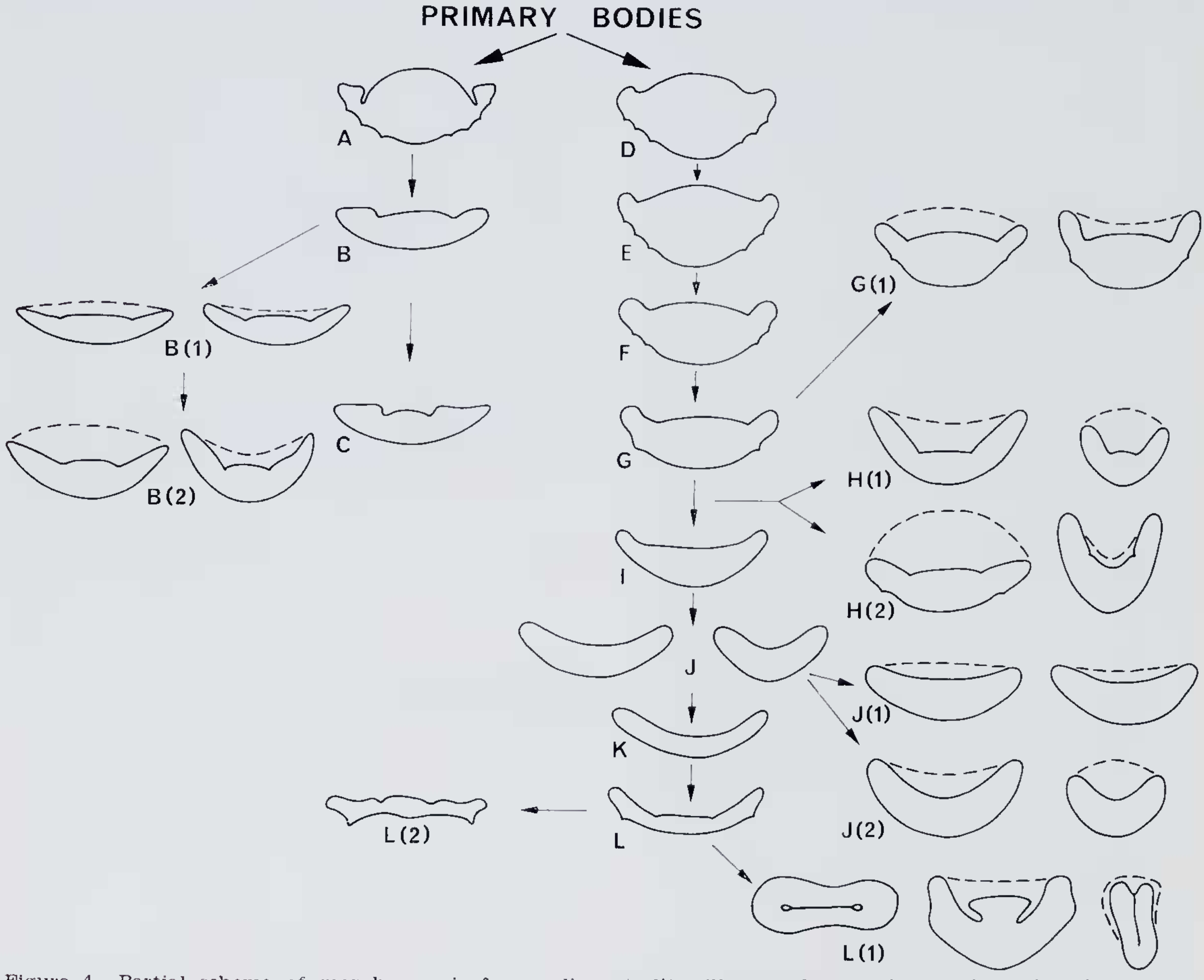

Figure 4.—Partial scheme of morphogenesis for small australites illustrated by vertical sections of uniform width to facilitate comparison, except that where two or more views are given, they are on the same scale for that particular specimen. Profiles of folded specimens added to sections as broken lines. Mass, diameter or length, locality and ownership stated except for specimens numbered 1-42, for details of which see Table 1. A.—Button with flat to concave posterior surface or flange, 2.74 g, 18.6 mm, Coolgardie W.A. (WASM 9465). B.—"Small" button, 0.146 g, 8.0 mm, Menangina Station, W.A. (WASM 10 613). B(1).—Longitudinal and cross sections of "small" button, very slightly folded, No. 2, Table 1. B(2).—Longitudinal and cross sections of "small" button or cored disc, gently folded. No. 1, Table 1. C.—Cored disc, 0.250 g, 9.7 mm, Port Campbell, Vic. (NMV E7830). D.—Flanged broad oval with convex posterior profile of flange, core emergent 1.5 mm above flange level, 1.82 g, 10.9 mm, Mt Remarkable Station, W.A. (KJ). E.—Button, core emergent 0.5 mm, 0.94 g, 11.9 mm, Mt Remarkable Station, W.A. (KJ). F.—Cored bowl, core 0.2 mm below flange level, 0.64 g, 11.2 mm, Mt Remarkable Station, W.A. (KJ). G.—Bowl, posterior surface faintly convex, No. 9, Table 1. G(1).—Longitudinal and transverse sections of a bowl, general type of G, gently folded, No. 10, Table 1. H(1).—Longitudinal and transverse sections of boat-shaped bowl with traces of outline of core, gently folded on longitudinal axis, No. 34, Table 1. H(2).—Round bowl with traces of outline of core, folding half completed, No. 7, Table 1. I.— Broad oval shallow bowl with concave posterior surface, 0.520 g, 11.0 mm, Menangina Station, W.A. (WASM 10 614). J.—Longitudinal and transverse sections of narrow oval bowl, No. 29, Table 1. J(1).—Longitudinal and transverse sections of round bowl (type of J) very slightly folded, No. 5, Table 1. J(2).—Longitudinal and transverse sections of narrow oval bowl (type of J) gently folded on transverse axis, No. 28, Table 1. K.—Longitudinal section of narrow oval bowl, No. 25, Table 1. L.—Restoration of highly thinned bowl shown in L(2) on presumption that it is frontally collapsed. Note prominent flow ridge. L(1).—Plan, longitudinal and transverse sections of completely folded thin bowl, walls 1.3 mm thick, gas escape tubules about half millimetre diameter, 0.358 g, 11.0 mm, Linton, Vic. (BM 1926, 316). Reference Dunn (1916). L(2).—Transverse section of frontally-collapsed, broad oval, thin bowl, now disc-like, 0.636 g, 14.5 mm, Port Campbell, Vic. (NMV E7821).

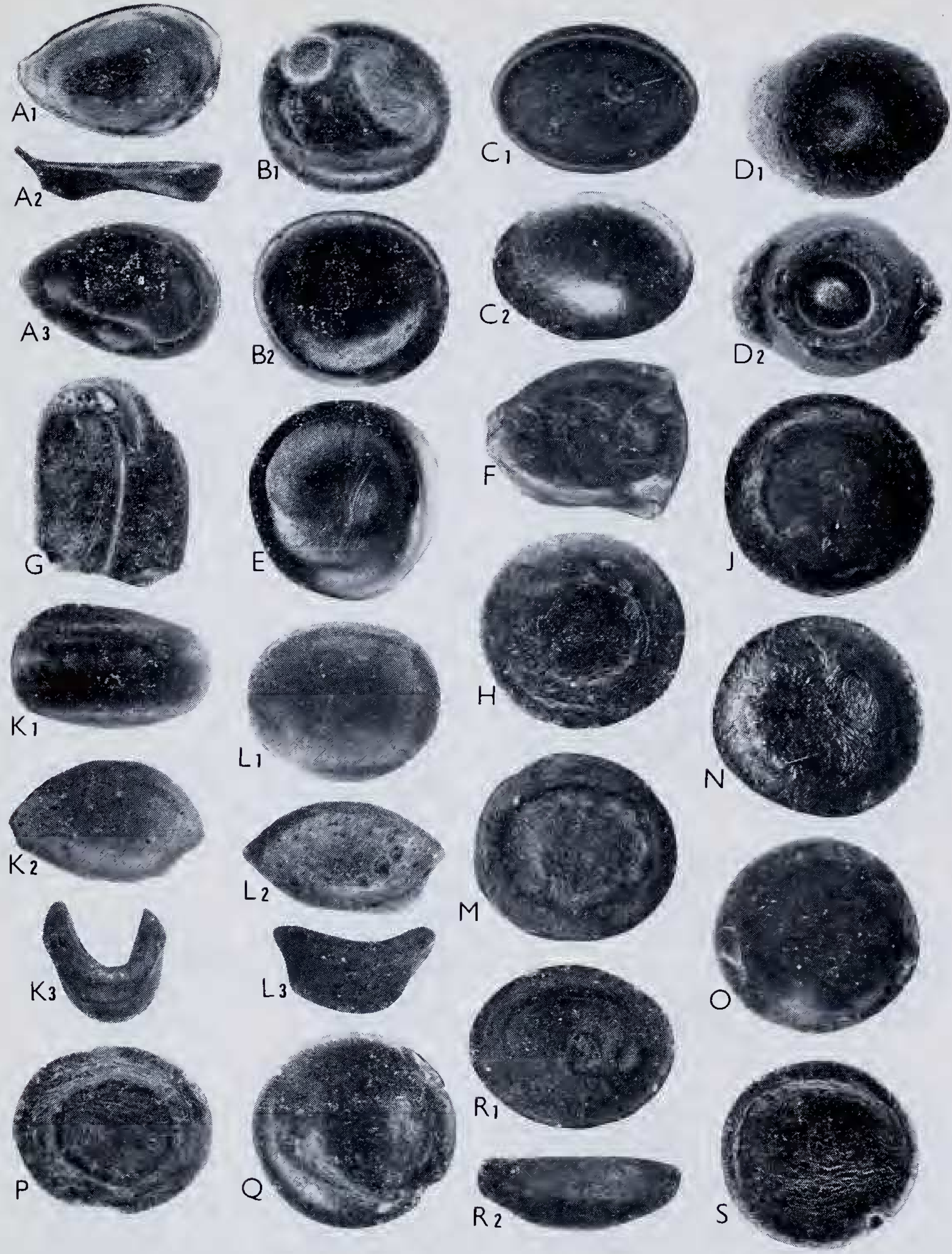

Figure 5.—Australites from Western Australia and Victoria. Illustrations are plan views (i.e. posterior surfaces of flight) unless stated otherwise. For details of specimens numbered 1-42, see Table 1. Scales vary slightly and may be judged by the dimensions given here or in Table 1. A1.—Teardrop bowl, length 13.4 mm, Menangina Station, W.A. (WASM 10 609). A2.—Side elevation of A1 showing frontal collapse. A3.—Anterior surface of A1 showing limitation of collapse by flow ridge. B1.—Broad oval, "tray" type, length 10.9 mm, Menangina Station, W.A. (WASM 10 614). B2.—Anterior surface of B1 showing frontal collapse. C1.—Narrow oval "tray" type, length 9.0 mm, Menangina Station, W.A. (WASM 10 609). C2.—Anterior surface of C1 showing frontal collapse. D1.—Anterior surface of fragment of hollow button, length 11.5 mm, Mt Remarkable Station, W.A. (KJ). Central collapse dimple over bubble cavity. D2.—Posterior view of D1 showing boss resulting from frontal collapse within breached bubble cavity. E.—Anterior surface of frontally collapsed broad oval bowl from Port Campbell, Vic. (NMV E7821). For details see Table 2. For transverse section see Fig. 4-L2. F.—Pine-seed form, length 10.6 mm, Earaheedy Station, W.A. (WASM 10 943). Flange broken from left end, overfolded at right end and fused to body which is visible through it. G.—Fragment of elongated "tray" type australite with thickened edge, length 9.0 mm, fold hinge along right-hand edge, i.e. right hand half of visible surface is anterior surface of flight. Mt Remarkable Station, W.A. (KJ). H.—No. 2. J.—No. 3. K1 to K3.—Plan, side and end elevations of No. 6. L1 to L3.—Plan, side and end elevations of No. 8. M.—No. 10. N.—No. 12. O.—No. 13 P.—No. 14. Q.—No. 15. R1 and R2.—Plan and side elevations of No. 16. S.—No. 18.

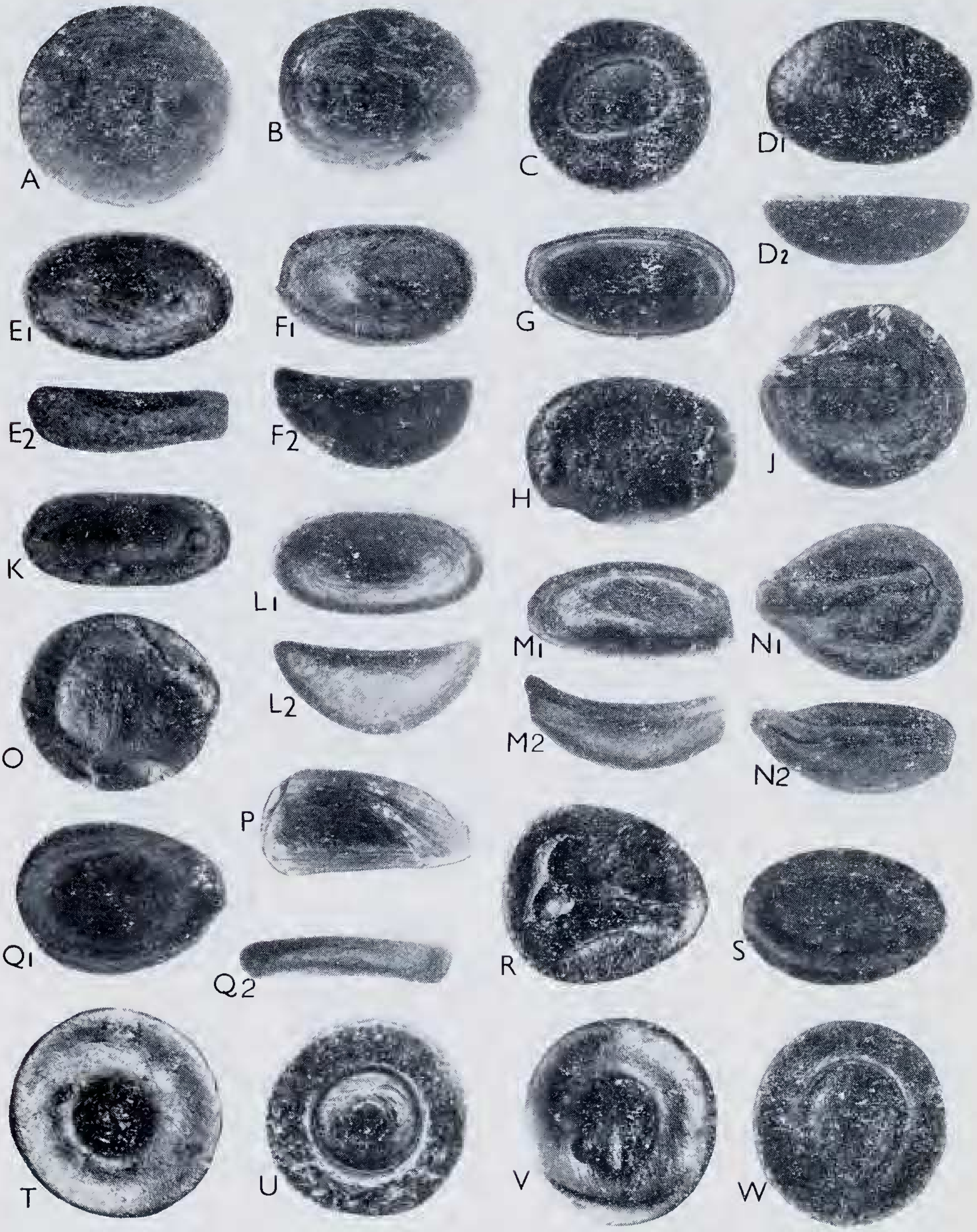

Figure 6.—Australites from Western Australia and Victoria. Illustrations are plan views (i.e. posterior surfaces of flight) unless stated otherwise. For details of specimens numbered 1-42, see Table 1. Scales vary slightly and may be judged by the dimensions given here or in Table 1. A.—No. 22. B.—No. 23. C.—No. 24. D1 and D2.—Plan and side elevation of No. 26. E1 and E2.—Plan and side elevation of No. 27. F1 and F2.—Plan and side elevation of No. 28. G.—No. 30. H.—No. 31. J.—No. 32. K.—No. 33. L1 and L2.—Plan and side elevation of No. 34. M1 and M2.—Plan and side elevation of No. 35. N1.—No. 38, showing overfolded tail fused to posterior surface. N2.—Oblique view of N1 showing hinge. O.—No. 39. P.—No. 40, showing thin, tapering, strap-like feature, possibly portion of overfolded tail, fused obliquely across posterior surface. Q1 and Q2.—Plan and side elevation of No. 41. R.—No. 42. S.—"Tray" form, length 15.2 mm, Menangina Station W.A. (WASM 10 613). T.—Cored disc, Port Campbell, Vic. (NMV E7830). See Table 2. U.—"Small" button, Menangina Station, W.A. See Pair 1, Table 2. V.—Teardrop plate with oval flange, Port Campbell, Vic. (NMV E7837). See Table 2. W.—No. 36. See also Pair 3, Table 2.

low wall around the posterior surface. The posterior surfaces are flat or gently concave (Fig. 3A, B, 6S). Frontally collapsed examples are shown in Figure 5B, C and a folded example in Figure 5G.

2. "Massive" forms with tray-like top, having a stout body and also showing the low posterior wall formed from overflowed melt (Fig. 3C). These also include elongated examples such as that having the general form of the swingboat of the fairground (Figs. 3D, 6M).

3. Very shallow bowls with outwardly-directed secondary growth, sometimes approximating to plano-convex form (Figs. 3E-H, 6A, B).

The relationships of these forms to the commoner small forms are not evident. It is tempting to see significance in the absence of well-developed discs of the type found in Victoria and the presence of these other forms in Western Australia in contrast to almost the opposite situation in eastern Australia. However, I have noticed a broad oval specimen of "Type" 1 and a round specimen of "Type" 2 amongst South Australian specimens. More likely, the rigorous weathering and erosion in interior Western Australia coupled with a lack of reporting of eastern Australian examples of the other forms are responsible.

A further minor mystery concerning small australites is that all the major plan-view shapes of larger australites are represented except the dumbbell. No "small" flanged dumbbells, dumbbell plates or bowls are present amongst the specimens examined. Nor do they appear to have been reported from elsewhere. It is suggested that the prominence of the gibbosities rendered them especially liable to ablation losses and that the typical shape was lost when size reduction was severe. It has been noticed that even specimens of mass 10 g are sometimes boat-shaped in plan view, though still showing a dip in the posterior profile as seen in side elevation, an indication of their derivation from dumbbell primary bodies.

Conclusions

A scheme of morphogenesis for small australites with two main lineages and side branches resulting from folding is presented in Fig. 4. Eastern Goldfields examples have been used in illustration if available. The scheme should be regarded as a summary of some of the suggestions which have been made and tentative in the extreme.

The range of posterior profile of flange from strongly convex to concave is related to increasingly severe deceleration (Chapman 1964). The two lineages of small australite development should perhaps be regarded as the ends of a whole spectrum of behaviour. The plano-convex type is a possible intermediate lineage.

No apology is offered for not having solved the problems of small-australite morphogenesis as a result of examining some weathered specimens from the Eastern Goldfields. The dearth of material and the considerable variety within that which is available leave the student groping for a pattern. What are presently "missing links" in morphological series may be found. Though there appear to be continuous button-disc and button-bowl morphological series, each individual is the final product of a different combination of size of primary body, entry velocity, incident angle or other variable. A morphological series of different individuals is not necessarily a developmental series. For example, there can be no certainty that a cored disc evolved through the "small" button form which, for a different primary body, was the final form. The true "missing links" of development will be forever missing because they had only a transitory existence during flight. The sectioning of some specimens for examination of the internal flow lines might well be informative but destructive examination of this rare material has thus far been avoided. It remains true as it was prior to this study that the collecting and recording of more small forms is needed before their types can be more clearly defined and a comprehensive scheme of morphogenesis can be proposed with any degree of confidence.

Acknowledgments.—I thank Dr R. Hutchison of the British Museum (Natural History), Dr W. D. Birch (National Museum of Victoria), Miss J. M. Scrymgour (South Australian Museum), Professor J. F. Lovering (University of Melbourne), Mr M. H. Lloyd (W.A. School of Mines), Mr and Mrs R. G. Tillotson, Mr D. J. Tillotson, Mr K. Jenkins, Mr J. L. C. Jones and Mr P. J. Simmonds for the loan of specimens in their charge or in their private collections. For the processing of the large number of my photographs of varied scales and qualities, I am especially grateful to Mr M. K. Quartermaine.

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